Annual Report

Project: NASA AISRP NNG04GP89G

Title: Block-Adaptive Parallel Implicit Methods for Semirelativistic Multifluid Hall-MHD

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Performance Period: October 1, 2004 through June 30, 2006

During the first two years of this project we accomplished significant progress in several areas:

1. Implementation and application of general resistivity models in the high-performance, adaptive MHD code, BATS-R-US,
2. Implementation and application of a multispecies MHD technique, and
3. Implementation of Hall MHD in BATS-R-US.

Significant progress has been accomplished in all three areas. Below we summarize our main accomplishments in more detail.

1. We developed and implemented a new method to include resistivity effects in MHD. This technique ensures conservation of mass, momentum, energy and magnetic flux even for complicated, time-dependent resistivity models. The method has been implemented in the BATS-R-US parallel adaptive MHD code as well as in the Space Weather Modeling Framework (SWMF). The application of this new technique resulted in several science publications and presentations.
2. We developed a new, conservative method to solve the multispecies MHD equations and implemented the method in BATS-R-US and SWMF. The method has been applied to Saturn and Mars, two high priority target of NASA. The new method has been used to accomplish new scientific results that were published in peer-reviewed journals and presented at national and international conferences. It should be noted that one of the publications was in Science, the most prestigious peer reviewed journal.
3. In the second year of the project we implemented the Hall MHD term in BATS-R-US and presently are in the process of extensive testing. The implementation ensures high computational performance, excellent parallel scaling and it is compatible with the general philosophy of block-adaptive AMR. In Hall MHD the electric field is modified from the resistive MHD expression by including the Hall term, jxB/n (j=electric current density, B=magnetic field, n=concentration). This seemingly simple modification is quite challenging to implement in a conservative, accurate and efficient manner. There are at least two challenges: (i) there is a second order spatial derivative that cannot be rewritten into a simple Laplace operator, and (ii) the maximum wave speed of the equation increases from the fast magnetosonic wave to the whistler wave speed that is approximately inversely proportional to the wave length. The first problem is especially difficult because of the adaptive block structure of the BATSRUS code. It took a lot of careful derivation and algorithmic development to obtain a spatially second order

accurate discretization at resolution changes. The second problem is also very important, because it limits the maximum explicit time step to extremely small values. It was solved by using a very efficient implicit time-stepping method.

Publications

1. I. V. Sokolov, K. G. Powell, T. I. Gombosi, aand I. I. Roussev, A TVD Principle and Conservative TVD Schemes for Adaptive Cartesian Grids, *J. Comp. Phys.*, submitted, 2006.
2. G. Toth, D.L. De Zeeuw, T.I. Gombosi, and K.G. Powell, A parallel explicit/implicit time stepping scheme on block-adaptive grids, *J. Comput. Phys.*, in press, 2006.
3. G. Toth, I. V. Sokolov, T. I. Gombosi, D, R. Chesney, C. R. Clauer, D. L. De Zeeuw, K. C. Hansen, K. J. Kane, W. B. Manchester, R. C. Oehmke, K. G. Powell, A. J. Ridley, I. I. Roussev, Q. F. Stout, O. Volberg, R. A. Wolf, S. Sazykin, A. Chan, and Bin Yu, Space Weather Modeling Framework: A new tool for the space science community*, J. Geophys. Res.*, *110*, A12226, doi:10.1029/2005JA011126, 2005.
4. M. Watanabe, K. Kabin, G. J. Sofko, R. Rankin, T. I. Gombosi, A. J. Ridley, and C. R. Clauer, Internal reconnection for northward interplanetary magnetic field, *J. Geophys. Res.*, 110, A06210, doi:10.1029/2004JA010832, 2005.
5. T.I. Gombosi and K.C. Hansen, Saturn's Variable Magnetosphere. *Science*, 307, 1224-1226, 2005.
6. Y. Ma, A. F. Nagy, I. V. Sokolov and K. C. Hansen,3D multi-species, high spatial resolution MHD studies of the solar wind interaction with Mars, *J. Geophys. Res., 109*, A07211, doi:10.1029/2003JA010367, 2004.
7. Y. Ma, A. F Nagy, T. E. Cravens, I. V Sokolov, J. Clark, and K. C. Hansen, 3D Global MHD model Prediction of the first close flyby of Titan by Cassini, *Geophys. Res. Lett., 31*, 10.1029/2004GL021215, 2004.

Invited Presentations

1. T.I. Gombosi, End-to-end space weather simulations with SWMF, Space Weather Week, Boulder, CO, April 25-28, 2006.
2. T. I. Gombosi, G. Toth, I. V. Sokolov, W. B. Manchester, A. J. Ridley, I. I. Roussev, D. L. De Zeeuw, K. C. Hansen, K. G. Powell, and Q. F. Stout, Halloween Storm Simulations with the Space Weather Modeling Framework, 44th AIAA Aerospace Sciences Meeting, Reno, Nevada, January 9-12, 2006.
3. T.I. Gombosi, Severe weather in space, NASA ESTO Technology Conference, Adelphi, MD, June 28-30, 2005.
4. T.I. Gombosi, D.L. De Zeeuw, I.V. Sokolov, G. Tóth, A.J. Ridley, K.C. Hansen, W.B. Manchester, I.I. Roussev, C.R. Clauer, K.G. Powell, Q.F. Stout, B. van Leer, P.L. Roe, Parallel, Adaptive, Coupled Plasma Simulations, Multiscale Processes in Fusion Plasmas, IPAM UCLA, Los Angeles, CA, January, 2005.

Contributed Talks

1. M.M. Kuznetsova, M. Hesse, L. Rastatter, G. Toth, D.L. De Zeeuw, T.I. Gombosi, Multi-Scale Modeling of Magnetospheric Reconnection, 2006 Spring AGU Meeting, Baltimore, MD, May 23-26, 2006.
2. Y. Jia, M.R. Combi, K.C. Hansen, T.I. Gombosi, A Multispecies MHD Model for the Interaction of Io's Atmosphere with the Jupiter Plasma Torus 2006 Spring AGU Meeting, Baltimore, MD, May 23-26, 2006.
3. A. Taktakishvili, M. Kuznetsova, M. Hesse, L. Rastatter, G. Toth, D. De Zeeuw, T. Gombosi, Magnetotail Current Sheet Thinning in Global Simulations of Magnetosphere Dynamics, 2005 Fall AGU Meeting, San Francisco, CA, December 5-9, 2005.
4. M. M. Kuznetsova, M. Hesse, L. Rastatter, G. Toth, D. De Zeeuw, T. Gombosi, Magnetic Reconnection in Global MHD Modeling of Magnetosphere Dynamics, 2005 Fall AGU Meeting, San Francisco, CA, December 5-9, 2005.
5. M.M. Kuznetsova, Hesse, M., Rastaetter, L., Toth, G., De Zeeuw, D. L., Gombosi, T. I., Fast Magnetotail Reconnection: Challenge to Global MHD Modeling, 2005 Spring AGU Meeting, New Orleans, LA, May 23-27, 2005.
6. M.M. Kuznetsova, Hesse, M., Rastaetter, L., Gombosi, T. I., Intermittent Reconnection, Flux Ropes and Vortices Generation at the Dayside Magnetopause, 2004 Fall AGU Meeting, San Francisco, CA, December 13-17, 2004.